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NASA TM X-1549

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SIMULATOR STUDY OF PILOT CONTROL OVER THE LUNAR MODULE DURING ASCENT FROM THE LUNAR SURFACE BY USING VISUAL GUIDANCE CUES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1968

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SUMMARY

A fixed-base simulator study was conducted to determine the ability of pilots to use a simple, visually guided piloting procedure to inject the ascent stage of the lunar module into a safe transfer orbit which had an apocynthion altitude of 80 nautical miles (148.16 kilometers). The pilot had control of the thrust along the longitudinal axis by means of an on-off switch and of the vehicle attitude by means of a rate-command or a rate-command—attitude-hold control system. The guidance procedure required the pilot to maintain three consecutive constant angles between the thrust axis and the line of sight to the down-range horizon, and to use an integrating accelerometer to indicate when to change the vehicle pitch attitude and when to terminate the thrust.

The results showed that the pilot could perform the tasks required for a simulated launch and transfer-orbit injection by using visual references for guidance. The resulting transfer orbits, however, differed appreciably and depend on whether the thrust was alined or misalined with the center of gravity as well as on the type of control system employed. An error analysis indicated that appreciable pilot-control problems were created when the rate-command control system was used in combination with thrust misalinement, that nonvertical-launch effects were of no consequence and easily controlled, and that thrust errors as large as 2 percent did not affect the safety of the ascent.

INTRODUCTION

One of the present concepts for accomplishing the lunar ascent to complete a rendezvous involves establishing initially a circular orbit at 50 000 feet (15 240 meters) and then a transfer orbit to 80 nautical miles (148.16 kilometers) when the orbiting command-service module is in the proper position relative to the lunar module (LM). Spacecraft control for the LM during this part of the lunar mission will be provided by automatic guidance and control systems; however, astronaut survival demands that the lunar launch take place and transfer orbit be established with or without the use of automatic control systems. Thus, simplified guidance procedures that use pilot control and a minimum of instrumentation are required for possible contingencies. Under normal conditions, these piloting procedures could also be used to monitor the performance of the automatic control modes or could be considered for primary control modes if such piloting procedures prove reliable.

The analytical study in reference 1 developed a planar ascent procedure to an 80-nautical-mile (148.16-kilometer) circular orbit by using several constant angles held relative to the lunar horizon for specified periods of time. The purpose of the present fixed-base simulator study was to examine, by using six-degree-of-freedom equations, the ability of pilots to employ the piloting procedures in reference 1 to perform a direct ascent from the lunar surface to injection into a Hohmann orbit which has an apocynthion altitude of 80 nautical miles (148.16 kilometers).

An integrating accelerometer mounted along the thrust axis was used instead of time to indicate when to orient the vehicle at different angles relative to the horizon and when to terminate the thrust. Out-of-plane angular guidance cues were obtained by using a star. Use of a star for yaw reference is possible only when lighting conditions are such that lunar-surface brightness will not obscure the stars; however, if the surface brightness is of high intensity, the astronaut might be able to use surface features for yaw reference.

SYMBOLS

Measurements of this investigation were made in U.S. Customary Units and are also given parenthetically in the International System of Units (SI). (See ref. 2.)

F	thrust, 3500 pounds (15 568.775 newtons)
f	fuel
g_e	gravitational acceleration at surface of earth, 32.2 feet/second^2 (9.8 meters/second^2)
g_m	gravitational acceleration at surface of moon, 5.32 feet/second^2 (1.62 meters/second^2)
h	altitude, feet (meters) or nautical miles (kilometers)
I_{sp}	assumed specific impulse of main thrust engine and attitude control jets, 306 seconds

K_{DR} angle between thrust axis and down-range horizon, degrees (radians)

l distance perpendicular to plane of reference orbit, feet (meters)

m mass, slugs (kilograms)

m_o assumed mass of LM at lunar surface, 329.192 slugs (4903 kilograms)

p,q,r vehicle angular rates about body axes, degrees/second (radians/second)

$R\dot{\overline{\theta}}$ circumferential velocity in reference orbit plane, feet/second (meters/second)

t time, seconds

V_c velocity gained as determined from fuel consumed, $g_e I_{sp} \log_e \frac{m_o}{m_o - \dot{m}t}$, feet/second (meters/second)

X_b, Y_b, Z_b body-axis system

x,y coordinates in body-axis system, inches (centimeters)

α_V initial alinement of vehicle in nominal pitch plane relative to local vertical, degrees (radians)

$\epsilon_{(\ )}$ error in conditions at thrust termination (actual value minus nominal value), subscript in parentheses indicates variable considered

θ angle of pitch, degrees (radians)

μ arithmetic mean

σ standard deviation from mean

ϕ angle of roll, degrees (radians)

ψ angle of yaw, degrees (radians)

Subscripts:

a conditions at apocynthion

j attitude control jets

N three-axis gimbal

p conditions at pericynthion

Abbreviations:

LM lunar module

RC rate command

RCAH rate command with attitude hold

A dot over a symbol indicates derivative with respect to time.

EQUATIONS OF MOTION

The equations of motion used in this study permitted six degrees of freedom of the LM. The force equations were derived in perturbation form about a circular orbit, which had an altitude of 500 000 feet (152 400 meters), and were written in a cylindrical coordinate system. The moment equations were written with respect to the body axes. The pilot closed the control loop and had direct input into the force and moment equations. Vehicle mass and moments of inertia were varied as thrust was applied to account for mass reduction during thrusting. Inertias for the ascent stage of the LM were used. Mass changes due to attitude control were neglected because they were small (about $0.029\ m_o$) in comparison to the mass change due to main thrust (about $0.469\ m_o$).

SIMULATOR

A three-axis gimbal system was mounted in a 40-foot-diameter (12.192-meter) sphere (figs. 1 and 2) and was used to simulate the body motions of the LM by controlling the projection of the moon horizon on the inner surface of the sphere. The horizon generator, a light source that projected through the circular aperture in the lower surface of a box, was mounted on the pitch axis of the gimbal. (See fig. 1.) The star ball, used to generate a star background, was also mounted on the pitch axis.

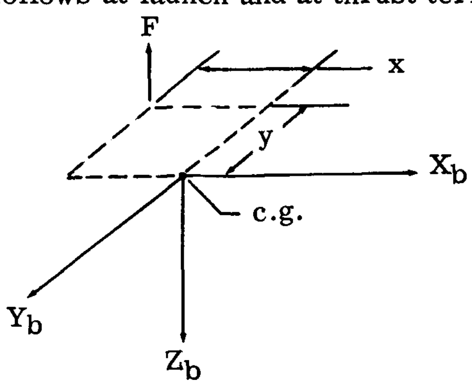
A full-scale mock-up of the cockpit section of the vehicle was placed in the sphere. Every effort was made in constructing this cockpit section to duplicate fields of view through the front and overhead windows of the LM. In the actual vehicle, the pilot wears an unpressurized pressure suit and is positioned in the cockpit as shown in figure 3. For these tests, however, the pilot was standing erect in a shirt-sleeve environment and was steadied by a pelvic restraint harness (fig. 4).

VEHICLE

The vehicle simulated in this study was the LM which has a single fixed engine thrusting along the Z_b-axis of symmetry (fig. 5). Thrust was applied at the maximum level or was off. The nominal thrust level of 3500 pounds (15 568 newtons) resulted in an initial vertical acceleration $\left(\frac{F}{m} - g_m\right)$ of $0.162g_e$. Specific impulse I_{sp} for the main engine and attitude control jets was assumed to be 306 seconds.

Center-of-Gravity Location

Two positions of the main thrust engine relative to the center of gravity were used. For the thrust-alined condition, the main thrust passed directly through the center of gravity and, thus, produced no moments about the center of gravity when the engine was thrusting. For the assumed thrust-misalined condition, the position of the main thrust varied linearly relative to the center of gravity as fuel was consumed and was located as follows at launch and at thrust termination:



At launch,

x = -1.5 in. (-3.81 cm)

y = -0.2 in. (-0.508 cm)

At thrust termination,

x = -2.8 in. (-7.11 cm)

y = -0.4 in. (-1.016 cm)

These offsets produced moments about the center of gravity when the engine was thrusting.

Control System

Although two hand controllers are shown in figure 6, the three-axis attitude controller located on the pilot's right was the only one used by the pilot in this simulation. When deflected, the controller created signals which simulated activation of pairs of jets producing positive or negative roll, pitch, and yaw moments about the X_b-, Y_b-, and

Z_b-axes, respectively. The controller was oriented for flying the vehicle with the pilot looking forward through the front window. When the pilot looked out the overhead window, yaw and roll attitude commands produced what appeared to be roll and yaw vehicle motions, respectively.

Two types of control modes were used and are characterized in the following table:

Control mode	Maximum rate commanded, deg/sec	Dead band	
		Rate, deg/sec	Position, deg
RC	20	0.75	--
RCAH	20	.75	0.3

Minimum Instrumentation

The meter labeled V_c (see fig. 6) was used in conjunction with overhead- and front-window grids for the minimum-instrumentation flights. The V_c meter was used to display the output of an integrating accelerometer mounted along the thrust axis of the vehicle. Preselected meter readings instead of time were used to indicate when to orient the vehicle at different angles relative to the horizon and when to terminate thrust; thus, a compensating effect was obtained for thrust magnitude errors. The resolution for the V_c meter was about ±25 feet/second (±7.62 meters/second). (See appendix for a description of the instrument panel used in the fully instrumented flights.)

Visual Aids

The visual aids used in this simulation consisted of double grids for the overhead and front windows (fig. 7). Double grids were used because lining up the gridlines for corresponding angles on each pane fixed the pilot's eye at the design eye position. The grids were graduated in 4° increments in pitch and 5° increments in yaw (fig. 8); however, vehicle pitch and yaw could be estimated to within about $1/2^\circ$. The lunar horizon was used for pitch and roll orientation, and a star, for yaw.

ASCENT TRAJECTORIES

The following table describes briefly the trajectory developed in reference 1 for a direct ascent to 80 nautical miles (148.16 kilometers) by assuming instantaneous vehicle angular positioning and by using the lunar horizon for thrust-vector orientation:

Time from launch, t, sec	Thrust orientation, K_{DR}, deg	V_c	
		ft/sec	m/sec
0 to 19.00	≈90.0 (vertical flight)	0 to 203	0 to 61.87
19.00 to 267.00	30.0	203 to 3348	61.87 to 1020.47
267.00 to 423.90	9.0	3348 to 6024	1020.47 to 1836.11
423.90 to 428.94*	7.6	6024 to 6124	1836.11 to 1866.59

*Main-engine thrust termination.

This trajectory was the nominal trajectory used for the piloted flights herein with one modification included. The LM pitchover after lift-off was initiated at 16 seconds instead of 19 seconds. Early pitchover was used because the LM attitude thrusters were of finite size; thus, a definite time was required to reorient the vehicle angular position. The resulting in-plane transfer orbit had an apocynthion biased high by about 10 nautical miles (18.52 kilometers).

Off-nominal trajectories were generated by varying the thrust level and take-off attitude. The variation in thrust level was ±2 percent from the nominal value of 3500 pounds (15 568 newtons), and a nonvertical launch of 3° in the nominal pitch plane was made.

PILOTING PROCEDURE

The piloting procedure developed in reference 1 was modified and used in this simulation. The coast segment and circularizing maneuver at 80 nautical miles (148.16 kilometers) were not attempted because of the time consumed during coast. The angle between the thrust vector and the down-range horizon was used for pitch guidance, and a star was used for yaw guidance during the powered parts of the ascent. Roll angle was controlled by maintaining the lunar horizon relatively straight across the overhead-window grid as shown in figure 8.

Fully Instrumented Flights

For the fully instrumented flights, the vehicle was guided during the ascent by using three guidance aids: (1) the position of the down-range horizon on the front- and overhead-window grids, (2) the instrument display shown in figure 9, and (3) a stopwatch to determine the times to change the thrust angle and to terminate the flight. One pilot (the command pilot) maintained vehicle orientation relative to the lunar horizon and scanned the instrument panel occasionally, while a second pilot was used to operate the stopwatch and relay critical times to the command pilot. The out-of-plane information displayed was yaw angle and displacement.

Minimum-Instrumentation Flights

The procedure for fully instrumented flights used in combination with errors in thrust magnitude could result in unacceptable terminal conditions; therefore, an integrating accelerometer, which is independent of the automatic guidance and control system, was simulated. The ascent procedure using the integrating accelerometer, the lunar horizon for pitch and roll guidance, and a star for yaw guidance was as follows for nominal and off-nominal thrust conditions: The position of the lunar horizon on the front-window grid was used to maintain a vertical-launch attitude. The position of a star was also noted for yaw reference. As the V_c-meter reading approached the nominal value of 171.57 feet/second (52.29 meters/second), the pilot initiated the first vehicle pitchover maneuver. In several seconds, the lunar horizon appeared in the overhead window and final adjustments were made to the vehicle orientation in pitch until the horizon was set at $K_{DR} = 30^{\circ}$. While maintaining this heading, the pilot monitored the position of a star and the lunar horizon for yaw and roll control, respectively, and occasionally glanced at the V_c meter.

When the V_c meter indicated approximately 3348 feet/second (1020.47 meters/second), a second pitchover maneuver was made to a thrust angle of 9° and this heading was held until the V_c meter indicated 6024 feet/second (1836.11 meters/second). At this time, a final pitchover maneuver was made to a thrust angle of 7.6°, which was held until the V_c meter indicated the end of the flight at 6124 feet/second (1866.59 meters/second)

RESULTS AND DISCUSSION

Most of the results of this investigation were obtained with the authors as test subjects. Several flight-research pilots made a limited number of flights on the simulator. Because the performance of the various pilots did not differ significantly, no distinction is made in the presentation of results.

Tabulated Results for All Data

The errors in the form of the arithmetic mean μ and the standard deviation from that mean σ are presented in table I for flights with full instrumentation and for other flight configurations with minimum instrumentation. The apocynthion h_a and pericynthion h_p altitudes of the resulting transfer orbits are tabulated. Also tabulated are K_{DR} for horizontal thrusting to circularize at h_a, and V_c to circularize at h_a. The parameters h_a, h_p, K_{DR} at h_a, and V_c at h_a are computed from the test data.

Table I has been arranged to permit a direct comparison of the results for the effects of the four basic test variables: the effects of thrust misalinement, control mode, thrust magnitude, and nonvertical launch.

Effect of l meter on out-of-plane results.- The comparison in table I of the full-instrumentation-flight data with the minimum-instrumentation data for $\epsilon_{(l)}$ shows the beneficial effects of using the l meter. (See instrument labeled l meter in fig. 9.) Use of this meter enabled the pilot to obtain mean out-of-plane distances l less than 1500 feet (457.2 meters) and standard deviations from the mean of about 1900 feet (579.12 meters) at flight termination. The use of a star to maintain a null out-of-plane angular orientation of the LM vehicle resulted in mean out-of-plane distances as great as 22 943 feet (6993.02 meters) with standard deviations from this mean of 24 043 feet (7328.30 meters). A star reference provided no out-of-plane displacement information; thus, the minimum-instrumentation flights gave some indication of the magnitudes that could be encountered in l if this variable is neglected in the ascent procedure. The use of surface features instead of the star would undoubtedly yield lower l values because a visual cue would be available for the pilot to use in controlling out-of-plane displacement.

Out-of-plane velocity results.- Mean out-of-plane velocity values $\epsilon_{(\dot{l})}$ and standard deviation from the mean were large for all flight conditions (≈50 feet/second (15.24 meters/second) for the mean and 100 feet/second (30.48 meters/second) for the standard deviation). For a successful rendezvous and docking, $\epsilon_{(\dot{l})}$ must be reduced to the order of 0.5 foot/second (0.15 meter/second) (ref. 3) and the proper orbital plane acquired. Further studies of the terminal rendezvous maneuver are required, however, to determine whether these out-of-plane velocities are excessive.

Resulting transfer orbits.- Transfer-orbit results (table I) show that the fully instrumented flights yielded average results fairly close to the reference trajectory. For these flights, the apocynthion standard deviation, which is a measure of the scatter of the resulting transfer trajectories about the mean, was approximately 12 nautical miles (22.22 kilometers). For the minimum-instrumentation flights with either control mode, slightly lower apocynthion values for the mean and standard deviations were obtained. The significance of the differences obtained is difficult to evaluate because of the number of task variables encountered and the limited number of flights made. Of importance, however, is the increased scatter of the resulting transfer trajectories when thrust was misalined. Thrust misalinement for both control modes resulted in apocynthion standard deviations between two and three times larger than those for the thrust-alined condition. Comparable results were obtained for pericynthion standard deviations; that is, thrust misalinement resulted in pericynthion deviations between two and three times larger than those for the thrust-alined condition. Thrust-variation results indicated that errors as large as 2 percent do not appear to be critical from a safety standpoint. The effect of nonvertical launch was of no consequence for the initial LM misalinement value used in this simulation.

Although considerable variations in transfer-orbit results were obtained for the minimum-instrumentation flights, safe orbits (defined herein as having a minimum altitude exceeding 30 000 feet (9144 meters)) were obtained for the different conditions investigated insofar as mean pericynthion altitudes were concerned. However, some pericynthion altitudes, which were below the assumed safe altitude of 30 000 feet (9144 meters), did occur when thrust was misalined. Safe orbits for these flights could be obtained by a velocity increase at the apocynthion of the transfer orbit. For all such flights, the velocity increase required was 4 feet/second (1.2 meters/second) or less. For those flights with the RC control mode, insufficient control fuel was available when the thrust was misalined to complete the ascent; hence, consideration of these transfer orbits is academic.

Because the individual transfer orbits varied appreciably in apocynthion values, an analytical examination was made of the amount of main engine fuel remaining in the LM when applied to additional maneuvers. Sufficient V_c was available for the main engine to circularize at h_a, if desired, and also to establish and to circularize another transfer orbit to 80 nautical miles (148.16 kilometers).

Thrust-misalinement effects.- Table II shows the fuel consumed by the attitude-control thrusters when the thrust was alined and misalined with the center of gravity for RCAH and RC control modes. The values indicate that thrust misalinement had more effect on the piloting task than any other condition shown in table II. For example, for the RCAH control mode, about six times more control fuel was consumed in attaining the desired transfer-orbit conditions of $V_c = 6124$ feet/second (1867 meters/second) when thrust was misalined with the center of gravity than when thrust was alined.

The piloting task for the RC control mode was more difficult, and with the assumed thrust misalinement, the amount of control fuel planned for the LM was insufficient to complete the ascent. Approximately 30 percent of the control fuel was used when the thrust was alined; whereas, 124 percent (24 percent more fuel than was available) was used when the thrust was misalined.

Control-mode effects.- A comparison of the RCAH and RC control modes in table II when the thrust is alined with the center of gravity shows that the RC control mode required about three times more attitude-control fuel than the RCAH control mode. Comparable results obtained for the thrust-misalined condition showed that twice as much fuel was used in the RC control mode and that the ascent could not be accomplished in this mode even though it could be accomplished in the RCAH control mode with a large expenditure of control fuel.

Pilot performance for maintaining K_{DR}.- The analog records for the control input angles $K_{DR} = 30^{\circ}$ and $K_{DR} = 9^{\circ}$ were analyzed to determine the ability of the pilot to maintain the correct guidance angles on the overhead grid. The differences between the values obtained by the pilot and the nominal values were used. The errors in the form of the arithmetic mean μ and standard deviation σ are presented in table III. The results in this form were difficult to discuss, and the data in table III were averaged for each of the five conditions, and are as follows:

Control mode	Thrust location relative to c.g.	Average value for:			
		$\epsilon(K_{DR}=30^{o})$, deg		$\epsilon(K_{DR}=9^{o})$, deg	
		μ	σ	μ	σ
Full-instrumentation flights					
RCAH	Alined	-1.05	0.44	-0.87	1.98
Minimum-instrumentation flights					
RCAH	Alined	0.53	0.81	-0.07	0.69
RCAH	Misalined	.47	.79	.64	.76
RC	Alined	-.70	1.10	-.21	.95
RC	Misalined	.36	1.97	.55	1.27

These results show that the pilot did a better job flying the vehicle during the minimum-instrumentation flights than during the full-instrumentation flights. For the minimum-instrumentation flights, the pilot could concentrate more on holding the correct angle than for the fully instrumented flights, which required the pilot to divide his time between monitoring the overhead angle and the full-instrument panel. The average μ results for the minimum-instrumentation flights showed that generally the pilot held the angles about as closely to the correct value when making the ascent in the RC control mode as in the RCAH control mode; and that for both control modes, the second angle $\left(K_{DR} = 9^{o}\right)$ was held about as close to the correct value as the first angle $\left(K_{DR} = 30^{o}\right)$ despite the more uncomfortable head position required for the second angle (head tilted back almost 90^{o}).

Average σ values were slightly larger for the RC control mode when thrust was alined with center of gravity and considerably larger when thrust was misalined as compared with the σ values for the RCAH control modes with thrust alined or misalined. These σ results also indicated the increased difficulty of the piloting task when the RC control mode was used and, particularly, the difficulty caused by thrust misalinement. The increased piloting difficulty can be attributed to the larger and more frequent control inputs required to maintain the correct pitch angle. The pilot's comments in reference 3 indicate that the width of the dead band for the RC control mode may have caused the large control inputs and, thus, contributed to the difficulty of the piloting task and the attendant higher attitude fuel consumption.

Static tests, made to determine the pilot's ability to read the angle in the overhead window, showed that the angle read by the pilot varied from the true angle by an average of -0.56° with the standard deviation of 1.22°.

CONCLUDING REMARKS

A study has been made of a pilot's ability to use a simple, visually guided piloting procedure to perform a simulated launch of the lunar module and to inject the ascent stage into a transfer orbit which has an apocynthion altitude of 80 nautical miles (148.16 kilometers). The guidance procedure requires the pilot to maintain three consecutive constant angles between the thrust axis and the line of sight to the down-range horizon after vertical lift-off to thrust termination. Both front and overhead windows of the lunar module are used and double window grids are employed. Out-of-plane angular guidance cues are obtained by using a star. The effects of thrust alinement, attitude control mode, thrust magnitude, and nonvertical launch are briefly investigated by using an integrating accelerometer to indicate when to change the thrust angle and when to terminate the thrust. For comparison, some flights (one control mode and alined thrust) are made with a fully instrumented control panel.

Within the limits of the simulation, the results show that by using visual references for guidance the pilot can perform the simulated launch and transfer-orbit injection. The resulting transfer orbits, however, differ appreciably. For the fully instrumented flights (thrust alined with the center of gravity and rate-command—attitude-hold control mode employed), the resulting transfer orbits scatter about a mean that closely approximates the reference trajectory. Standard deviation in apocynthion altitude, which is indicative of scatter, is about 12 nautical miles (22.22 kilometers). In addition, out-of-plane displacements are small. With no instrumentation except the output of an integrating accelerometer, comparable transfer orbits are obtained with the same attitude control mode and thrust condition. Another control system examined is the rate command. Main-engine thrust misalinement for both control modes increases the scatter of the transfer orbits about the mean as indicated by apocynthion standard deviations between two and three times larger than for the thrust-alined condition. For flights with both control modes, out-of-plane displacements are considerably larger for minimum-instrumentation flights than for the fully instrumented flights in which out-of-plane displacements were controlled. Further studies of the terminal rendezvous maneuver are required to determine whether the out-of-plane velocities and displacements are excessive.

Although safe orbits are obtained insofar as mean pericynthion altitudes are concerned for all thrust conditions and control modes examined, some pericynthion altitudes below an assumed safe altitude of 30 000 feet (9144 meters) occur when thrust is misalined. For all such flights, the velocity increase of 4 feet/second (1.2 meters/second) or less at apocynthion insures safe orbits for these trajectories.

Of the two attitude control modes used, rate command is more difficult to use in controlling the vehicle during the ascent than the rate command with altitude hold when thrust is alined with the center of gravity. Thrust misalinement with center of gravity increases the difficulty of the piloting task in both control modes. In the rate-command control mode the pilot uses more than the available supply of control fuel to complete the ascent with the assumed misalinement.

Thrust-variation results indicate that errors as large as 2 percent do not appear to be critical from a safety standpoint. The effect of a 3° nonvertical launch in the nominal pitch plane is of no consequence. Results for pilot performance in maintaining the correct guidance angle show that the rate-command control mode exhibits appreciable control effects. Based on the pilot's comments in NASA TN D-3972, these control effects may be due to the large dead band used.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 21, 1967,
125-17-05-01-23.

APPENDIX

INSTRUMENT DISPLAY FOR FULLY INSTRUMENTED FLIGHTS

The instrument display for the fully instrumented flights was consistent with the pilot looking along the vehicle X_b-axis. The instrumentation shown in figure 9 and used in these flights was to some extent a general-purpose display which contained many of the instruments found in the lunar module. Fine resolution meters were added to the vehicle panel used in the present simulation to aid in pilot training and accurate readout of the quantities l, $\Delta R\dot{\bar{\theta}}$, and Δh at thrust termination.

All meters except the three-axis attitude indicator were single-needle meters. A scale-change toggle switch for the altitude-rate meter changed the scale from 0 to ±1000 feet/second (0 to ±304.8 meters/second) in the up position to 0 to ±100 feet/second (0 to ±30.48 meters/second) in the down position. A four-position switch allowed the pilot a choice of one of four scales for the altitude meter, which could display altitude to 1 000 000 feet (304 800 meters). For these tests, the switch was set so that altitude would be read from 0 to 10 000 feet (0 to 3048 meters) or from 0 to 100 000 feet (0 to 30 480 meters).

Of the three meters l, $\Delta R\dot{\bar{\theta}}$, and Δh at the bottom of the panel, the one labeled l was a direct-reading meter. The meters labeled $\Delta R\dot{\bar{\theta}}$ and Δh showed the variation from the following nominal values: 5484 feet/second (1671.52 meters/second) for $R\dot{\bar{\theta}}$ and 50 000 feet (15 240 meters) for h. A toggle switch changed the scales on the meters so that scales of 0 to ±5000 feet (0 to ±1524 meters) and 0 to ±50 000 feet (0 to ±15 240 meters) were available for l; 0 to ±50 feet/second (0 to ±15.24 meters/second) and 0 to ±500 feet/second (0 to ±152.4 meters/second), for $\Delta R\dot{\bar{\theta}}$; and 0 to ±500 feet (0 to ±152.4 meters) and 0 to ±5000 feet (0 to ±1524 meters), for Δh.

The quantities measured by the various instruments are summarized in the following table:

	Switch position	Scale range	Scale increment divisions
Pitch angle	---------------	0° to $\pm 90^{\circ}$	10°
Roll angle	---------------	0° to $\pm 90^{\circ}$	10°
Yaw angle	---------------	0° to $\pm 90^{\circ}$	10°
Circumferential velocity, $R\dot{\theta}$	Take-off	0 to 6000 ft/sec (0 to 1828.8 m/sec)	200 ft/sec (60.96 m/sec)
Rate of climb; also altitude rate, $\dot{h}$	Take-off Up	0 to ±1000 ft/sec (0 to ±304.8 m/sec)	20 ft/sec (6.096 m/sec)
	Take-off Down	0 to ±100 ft/sec (0 to ±30.48 m/sec)	2 ft/sec (0.6096 m/sec)
Altitude, h	2	0 to 10 000 ft (0 to 3048 m)	200 ft (60.96 m)
	3	0 to 100 000 ft (0 to 30 480 m)	2000 ft (609.6 m)
Main fuel remaining	---------------	0 to 100 percent	2 percent
Attitude-control fuel remaining	---------------	0 to 100 percent	2 percent
Roll rate, p	---------------	0 to ±20 deg/sec	2 deg/sec
Pitch rate, q	---------------	0 to ±20 deg/sec	2 deg/sec
Yaw rate, r	---------------	0 to ±20 deg/sec	2 deg/sec
Out-of-plane distance, l	Up	0 to ±50 000 ft (0 to ±15 240 m)	2000 ft (609.6 m)
	Down	0 to ±5000 ft (0 to ±1524 m)	200 ft (60.96 m)
$\Delta R\dot{\theta}$	Up	0 to ±500 ft/sec (0 to ±152.4 m/sec)	20 ft/sec (6.096 m/sec)
	Down	0 to ±50 ft/sec (0 to ±15.24 m/sec)	2 ft/sec (0.6096 m/sec)
Δh	Up	0 to ±5000 ft (0 to ±1524 m)	200 ft (60.96 m)
	Down	0 to ±500 ft (0 to ±152.4 m)	20 ft (6.096 m)
V_c	Right Automatic	0 to 8000 ft/sec (0 to 2438.4 m/sec)	50 ft/sec (76.2 m/sec)
	Right Switching	0 to 800 ft/sec (0 to 243.84 m/sec)	25 ft/sec (7.62 m/sec)

REFERENCES

1. Fletcher, Herman S.; and Barker, L. Keith: A Manual Method for Control of the Thrust Axis During Planar Ascent From the Lunar Surface to a Circular Orbit. NASA TN D-3681, 1966.

2. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.

3. Hatch, Howard G., Jr.; Pennington, Jack E.; and Cobb, Jere B.: Dynamic Simulation of Lunar Module Docking With Apollo Command Module in Lunar Orbit. NASA TN D-3972, 1967.

TABLE I.- SUMMARY OF RESULTS USING ARITHMETIC MEAN μ AND STANDARD DEVIATION FROM MEAN σ FOR PARAMETERS INVOLVED

(a) U.S. Customary Units

																			Resulting transfer-orbit conditions									
Number of flights	Thrust location relative to c.g.	Control mode	ΔF, percent	α_V, deg	$\epsilon(\dot{h})$, ft/sec		$\epsilon(h)$, ft		$\epsilon(R\dot{\theta})$, ft/sec		f_j used, percent		$\epsilon(V_c)$, ft/sec		$\epsilon(\dot{i})$, ft/sec		$\epsilon(i)$, ft		h_a, n. mi.		h_p, n. mi.		K_{DR} to circularize at h_a, deg		V_c to circularize at h_a, ft/sec			
					μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ		
Ascent data - full instrumentation																												
16	Alined	RCAH	0	0	7.92	17.51	-1337	2542	-2.00	16.63	13.10	3.84	2.01	7.49	50.69	110.40	1 417	1 833	82.08	11.73	7.81	0.58	23.07	1.58	100.53	14.94		
Effect of thrust misalinement on ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	8.79	10.33	816	3893	-3.44	13.44	9.74	4.34	-1.02	3.00	48.84	125.00	13 280	20 352	80.80	7.90	8.35	0.67	22.93	1.08	98.22	10.41		
14	Misalined	RCAH	0	0	20.16	31.13	2350	9599	-23.70	37.89	63.36	3.39	4.00	4.00	75.38	103.34	22 943	24 043	67.07	20.44	7.14	2.06	20.66	3.67	81.87	25.75		
12	Alined	RC	0	0	4.04	25.96	-358	2439	-8.00	11.72	31.61	6.96	-1.57	2.74	56.30	83.89	21 950	18 033	75.07	8.44	7.81	.58	22.15	1.17	91.66	10.88		
5	Misalined	RC	0	0	27.36	39.88	-2020	8843	-10.40	32.67	124.32	12.48	6.20	5.63	-16.44	194.00	-6 440	46 300	76.07	19.52	6.64	1.85	22.12	2.66	94.26	25.81		
Effect of control mode on ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	8.79	10.33	816	3893	-3.44	13.44	9.74	4.34	-1.02	3.00	48.84	125.00	13 280	20 352	80.80	7.90	8.35	0.67	22.93	1.08	98.22	10.41		
12	Alined	RC	0	0	4.04	25.96	-358	2439	-8.00	11.72	31.61	6.96	-1.57	2.74	56.30	83.89	21 950	18 033	75.07	8.44	7.81	.58	22.15	1.17	91.66	10.88		
14	Misalined	RCAH	0	0	20.16	31.13	2350	9599	-23.70	37.89	63.36	3.39	4.00	4.00	75.38	103.30	22 943	24 043	67.07	20.44	7.14	2.06	20.66	3.67	81.87	25.75		
5	Misalined	RC	0	0	27.36	39.88	-2020	8843	-10.40	32.67	124.32	12.48	6.20	5.63	-16.44	194.00	-6 440	46 300	76.07	19.52	6.64	1.85	22.12	2.66	94.26	25.81		
Effect of variation in thrust on ascent - minimum instrumentation																												
11	Misalined	RCAH	2	0	4.80	21.46	3581	3977	-14.90	15.76	61.89	2.22	9.00	5.60	138.90	167.30	17 900	10 694	75.00	7.95	8.58	0.56	22.14	1.12	90.48	10.76		
14	Misalined	RCAH	0	0	20.16	31.13	2350	9599	-23.70	37.89	63.36	3.39	4.00	4.00	75.38	103.30	22 943	24 043	67.07	20.44	7.14	2.06	20.66	3.67	81.87	25.75		
11	Misalined	RCAH	-2	0	-13.13	37.29	-7727	7344	-20.00	32.00	65.46	3.24	7.00	6.00	60.61	154.10	15 927	26 027	65.43	19.40	6.17	2.12	20.48	3.32	81.15	27.11		
Effect of nonvertical launch on ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	8.79	10.33	816	3893	-3.44	13.44	9.74	4.34	-1.02	3.00	48.84	125.00	13 280	20 352	80.80	7.90	8.35	0.67	22.93	1.08	98.22	10.41		
10	Alined	RCAH	0	3	-5.26	6.74	-1510	2745	6.40	7.70	9.76	3.98	-.18	1.20	68.95	75.90	17 500	17 221	85.60	5.14	7.95	.47	23.58	.66	104.91	6.92		

(b) International System of Units

																			Resulting transfer-orbit conditions									
Number of flights	Thrust location relative to c.g.	Control mode	ΔF, percent	α_V, deg	$\epsilon(\dot{h})$, m/sec		$\epsilon(h)$, m		$\epsilon(R\dot{\theta})$, m/sec		f_j used, percent		$\epsilon(V_c)$, m/sec		$\epsilon(\dot{i})$, m/sec		$\epsilon(i)$, m		h_a, km		h_p, km		K_{DR} to circularize at h_a, deg		V_c to circularize at h_a, m/sec			
					μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ		
Ascent data - full instrumentation																												
16	Alined	RCAH	0	0	2.41	5.34	-407	774	-0.61	5.06	13.10	3.84	0.61	2.28	15.45	33.64	431	558	152.01	21.72	14.46	1.07	23.07	1.58	30.64	4.55		
Effect of thrust misalinement on ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	2.68	3.15	248	1186	-1.05	4.09	9.74	4.34	-0.31	0.91	14.88	38.10	4047	6 203	149.64	14.63	15.46	1.24	22.93	1.08	29.93	3.17		
14	Misalined	RCAH	0	0	6.14	9.48	716	2926	-7.22	11.54	63.36	3.39	1.21	1.21	22.97	31.49	6993	7 328	124.21	37.85	13.22	3.81	20.66	3.67	24.95	7.84		
12	Alined	RC	0	0	1.23	7.91	-109	743	-2.44	3.57	31.61	6.96	-.48	.84	17.16	25.56	6690	5 496	139.02	15.63	14.46	1.07	22.15	1.17	27.93	3.31		
5	Misalined	RC	0	0	8.34	12.15	-615	2695	-3.17	9.95	124.32	12.48	1.89	1.72	-5.01	59.13	-1962	14 112	140.88	36.15	12.29	3.42	22.12	2.66	28.73	7.86		
Effect of control mode or ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	2.68	3.15	248	1186	-1.05	4.09	9.74	4.34	-0.31	0.91	14.88	38.10	4047	6 203	149.64	14.63	15.46	1.24	22.93	1.08	29.93	3.17		
12	Alined	RC	0	0	1.23	7.91	-109	743	-2.44	3.57	31.61	6.96	-.48	.84	17.16	25.56	6690	5 496	139.02	15.63	14.46	1.07	22.15	1.17	27.93	3.31		
14	Misalined	RCAH	0	0	6.14	9.48	716	2926	-7.22	11.54	63.36	3.39	1.21	1.21	22.97	31.49	6993	7 328	124.21	37.85	13.22	3.81	20.66	3.67	24.95	7.84		
5	Misalined	RC	0	0	8.34	12.15	-615	2695	-3.17	9.95	124.32	12.48	1.89	1.72	-5.01	59.13	-1962	14 112	140.88	36.15	12.29	3.42	22.12	2.66	28.73	7.86		
Effect of thrust variation on ascent - minimum instrumentation																												
11	Misalined	RCAH	2	0	1.46	6.54	1091	1212	-4.54	4.80	61.89	2.22	2.74	1.70	42.33	50.99	5455	3 259	138.90	14.72	15.89	1.03	22.14	1.12	27.57	3.27		
14	Misalined	RCAH	0	0	6.14	9.48	716	2926	-7.22	11.54	63.36	3.39	1.21	1.21	22.97	31.49	6993	7 328	124.21	37.85	13.22	3.81	20.66	3.67	24.95	7.84		
11	Misalined	RCAH	-2	0	-4.00	11.36	-2355	2238	-6.09	9.75	65.46	3.24	2.13	1.83	18.47	46.97	4854	7 933	121.17	35.92	11.42	3.92	20.48	3.32	24.73	8.26		
Effect of nonvertical launch on ascent - minimum instrumentation																												
25	Alined	RCAH	0	0	2.68	3.15	248	1186	-1.05	4.09	9.74	4.34	-0.31	0.91	14.88	38.10	4047	6 203	149.64	14.63	15.46	1.24	22.93	1.08	29.93	3.17		
10	Alined	RCAH	3	0	-1.60	2.05	-460	836	1.95	2.34	9.76	3.98	-.05	.36	21.01	23.13	5334	5 248	158.53	9.51	14.72	.87	23.58	.66	31.97	2.11		

TABLE II.- EFFECT OF THRUST MISALINEMENT, CONTROL MODE, THRUST VARIATION, AND NONVERTICAL LAUNCH ON FUEL CONSUMED BY ATTITUDE CONTROL JETS

α_V, deg	Control mode	Control fuel used, percent		Thrust location relative to c.g.	Variation of thrust, percent
		μ	σ		
Full instrumentation					
0	RCAH	13.10	3.84	Alined	0
Minimum instrumentation					
0	RCAH	9.74	4.34	Alined	0
0	RCAH	63.36	3.39	Misalined	0
0	RC	31.61	6.96	Alined	0
0	RC	124.32	12.48	Misalined	0
0	RCAH	9.74	4.34	Alined	0
0	RC	31.61	6.96	Alined	0
0	RCAH	63.36	3.39	Misalined	0
0	RC	124.32	12.48	Misalined	0
0	RCAH	61.89	2.22	Misalined	2
0	RCAH	63.36	3.39	Misalined	0
0	RCAH	65.46	3.24	Misalined	-2
0	RCAH	9.74	4.36	Alined	0
3	RCAH	9.76	3.98	Alined	0

TABLE III.- ARITHMETIC MEAN μ AND STANDARD DEVIATION σ OF DIFFERENCE BETWEEN VALUES OF K_{DR} HELD BY PILOT AND NOMINAL VALUES OF $K_{DR} = 30^{\circ}$ AND $K_{DR} = 9^{\circ}$

Control mode	Thrust location relative to c.g.	Data points per flight	$\epsilon_{(K_{DR}=30^{\circ})}$, deg		Data points per flight	$\epsilon_{(K_{DR}=9^{\circ})}$, deg	
			μ	σ		μ	σ
Full-instrumentation flights							
RCAH	Alined	25	-0.728	0.523	16	-1.525	3.507
		25	-1.204	.485	16	-.663	4.344
		25	-1.100	.579	16	-1.444	1.828
		25	-1.216	.335	16	.188	3.031
		25	-1.328	.496	16	-.806	.385
		25	-1.308	.492	16	-.975	1.667
		25	-.760	.355	16	-.975	.457
		25	-.764	.271	16	-.806	.621
Minimum-instrumentation flights							
RCAH	Alined	25	-0.77	0.50	16	-0.73	0.90
		25	.02	.32	16	-.46	.50
		25	-.48	.50	16	-.45	.50
		25	-.24	.80	16	-.74	.38
		25	-.96	.80	16	-.25	1.09
		24	-.39	1.93	16	1.16	.74
		24	-.54	.77	16	.54	.62
		24	-.92	.83	16	.34	.77
	Misalined	25	0.32	1.02	16	0.17	1.19
		25	.54	1.16	15	.77	.66
		22	.30	.33	17	1.03	.53
		24	1.00	.65	14	-.21	.94
		24	.48	.42	15	.87	.47
		24	1.04	.52	16	.59	.81
		25	0	.85	14	1.00	.77
		25	.10	1.41	16	.94	.68
RC	Alined	23	-1.34	0.76	16	-1.09	0.48
		24	-1.05	.58	15	-1.07	.70
		24	-1.25	.64	16	-1.13	.57
		25	-.84	.67	16	-1.28	.63
		24	-.50	1.84	16	1.18	1.04
		24	-.37	1.10	15	.11	1.84
		24	.06	1.02	16	1.44	.95
		25	-.34	2.19	15	.13	1.43
	Misalined	24	-0.63	1.82	16	0.95	1.52
		25	-1.15	2.02	16	.23	1.11
		25	1.44	2.14	16	.17	1.04
		24	1.54	2.23	16	-.10	1.90
		24	.60	1.66	16	1.50	.79

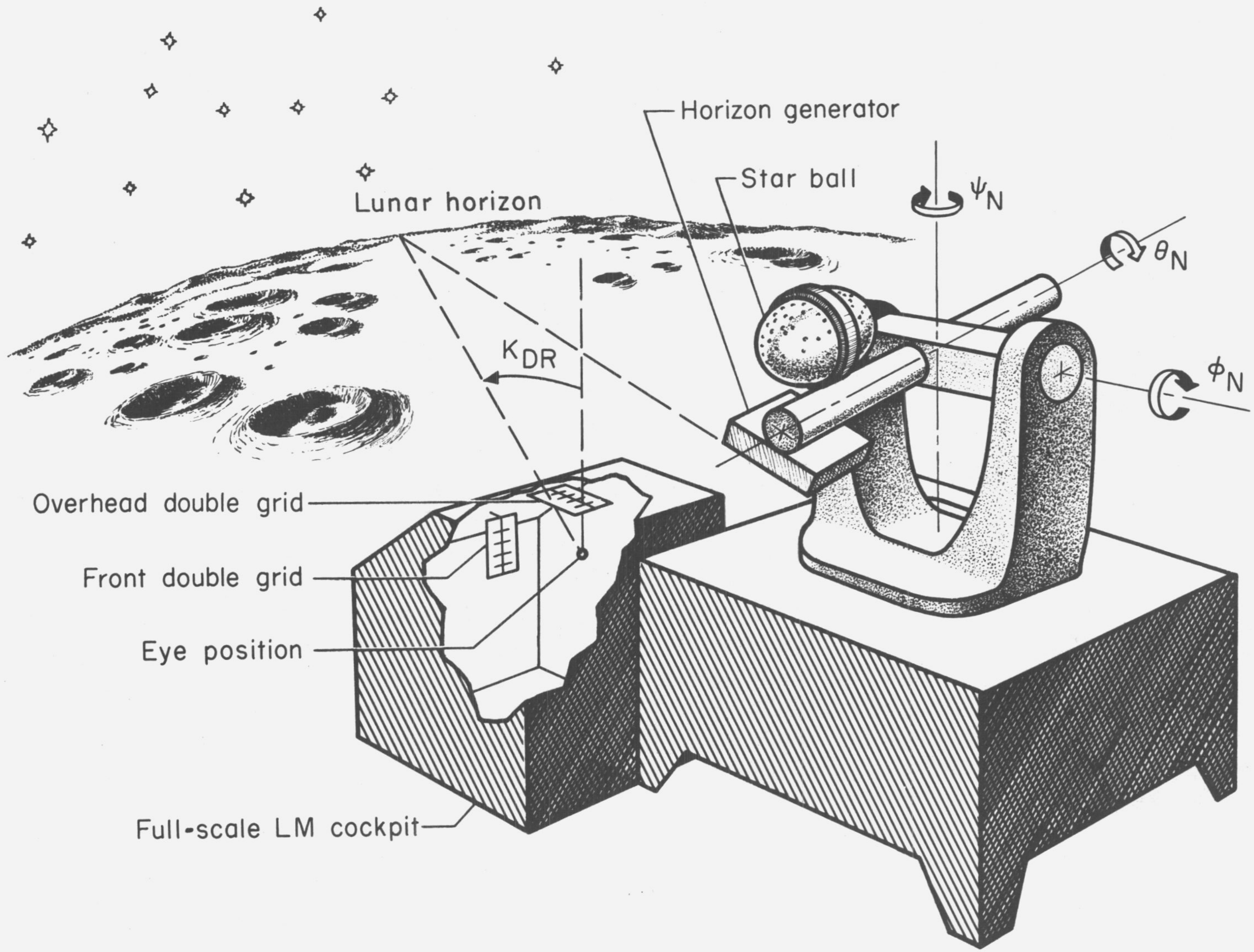


Figure 1.- Schematic drawing of complete setup with relative positions of three-axis gimbal system, cockpit, and lunar horizon.

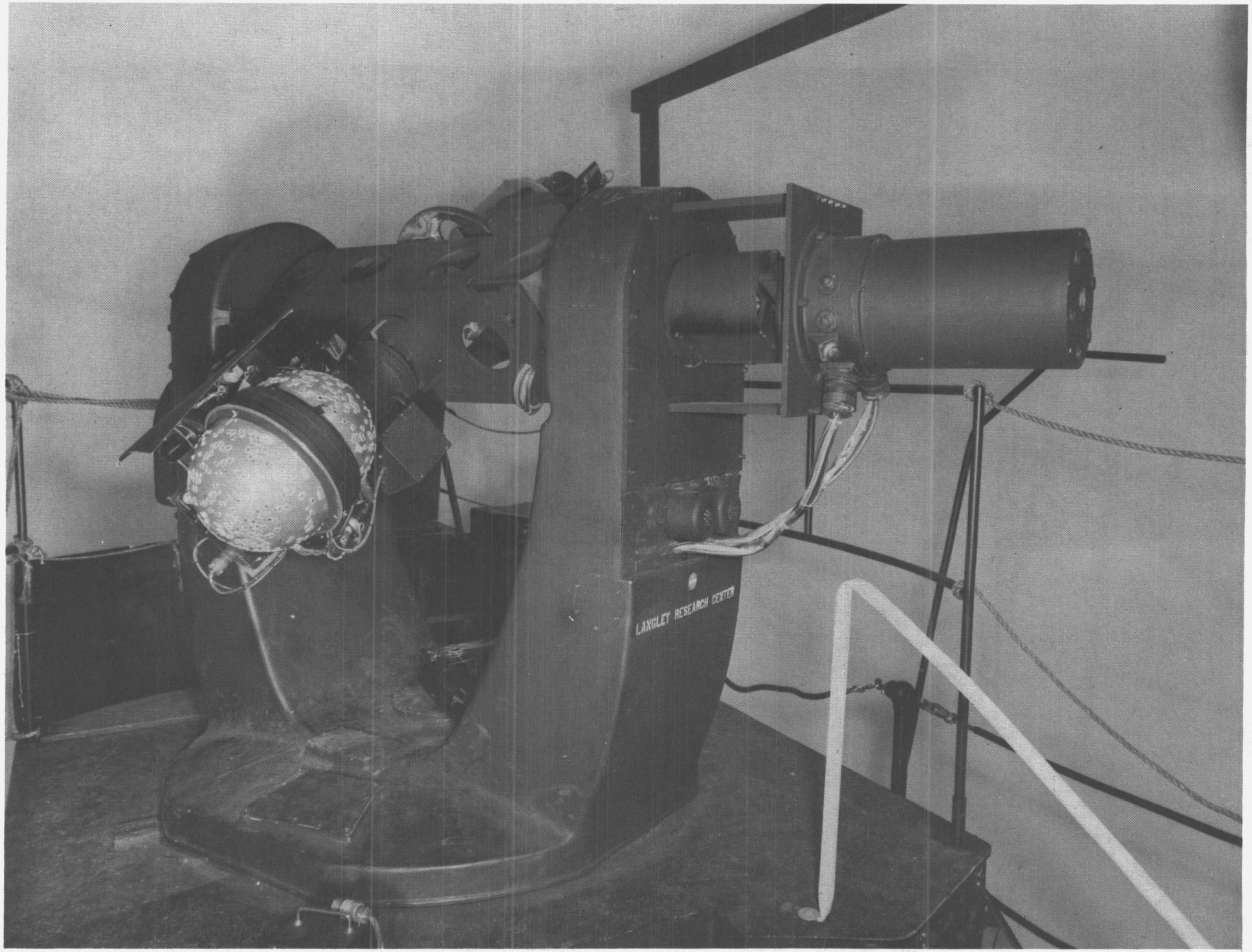
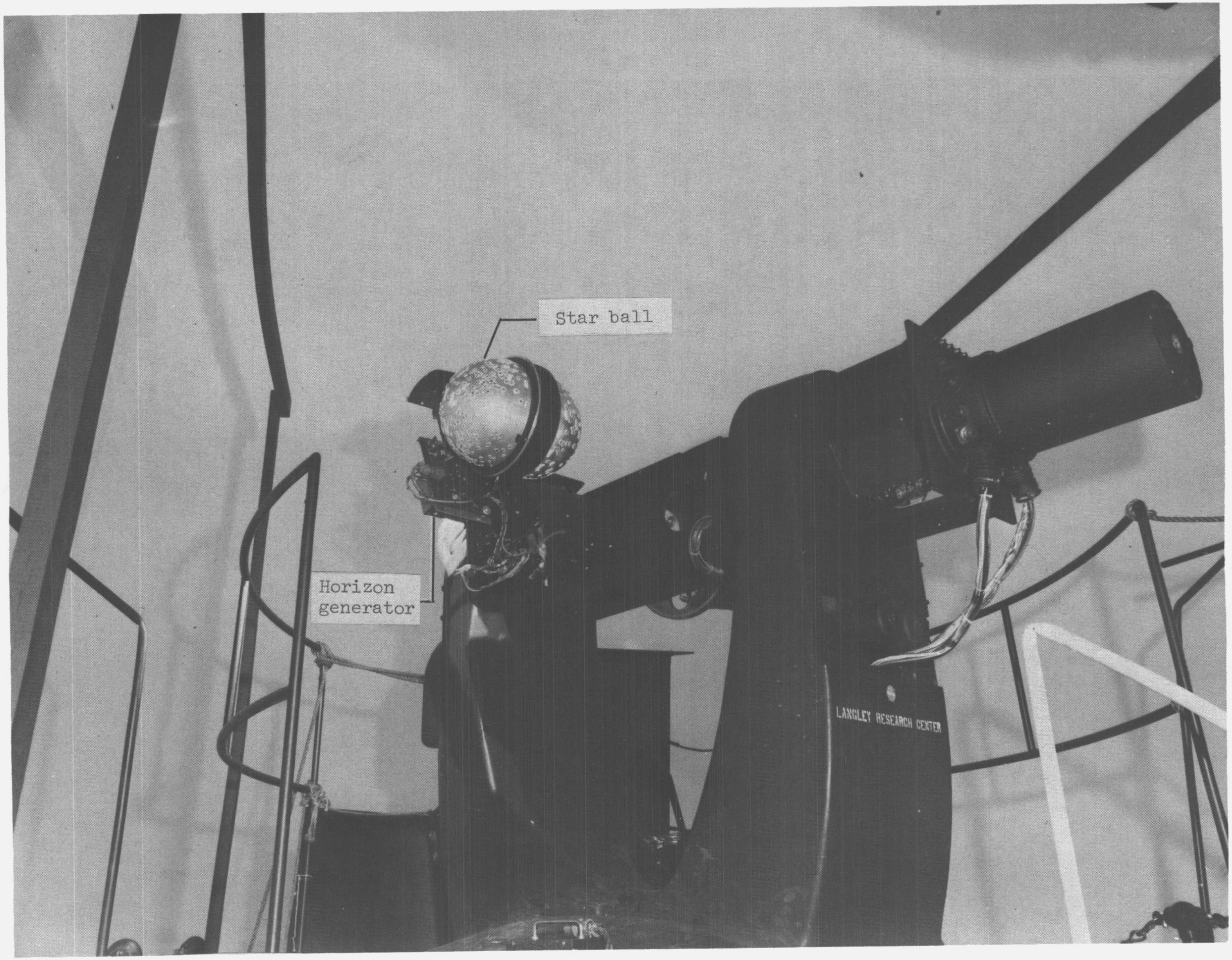


Figure 2.- Three-axis gimbal system and simulated lunar horizon. L-66-10107



L-66-10109.1

Figure 2.- Continued.

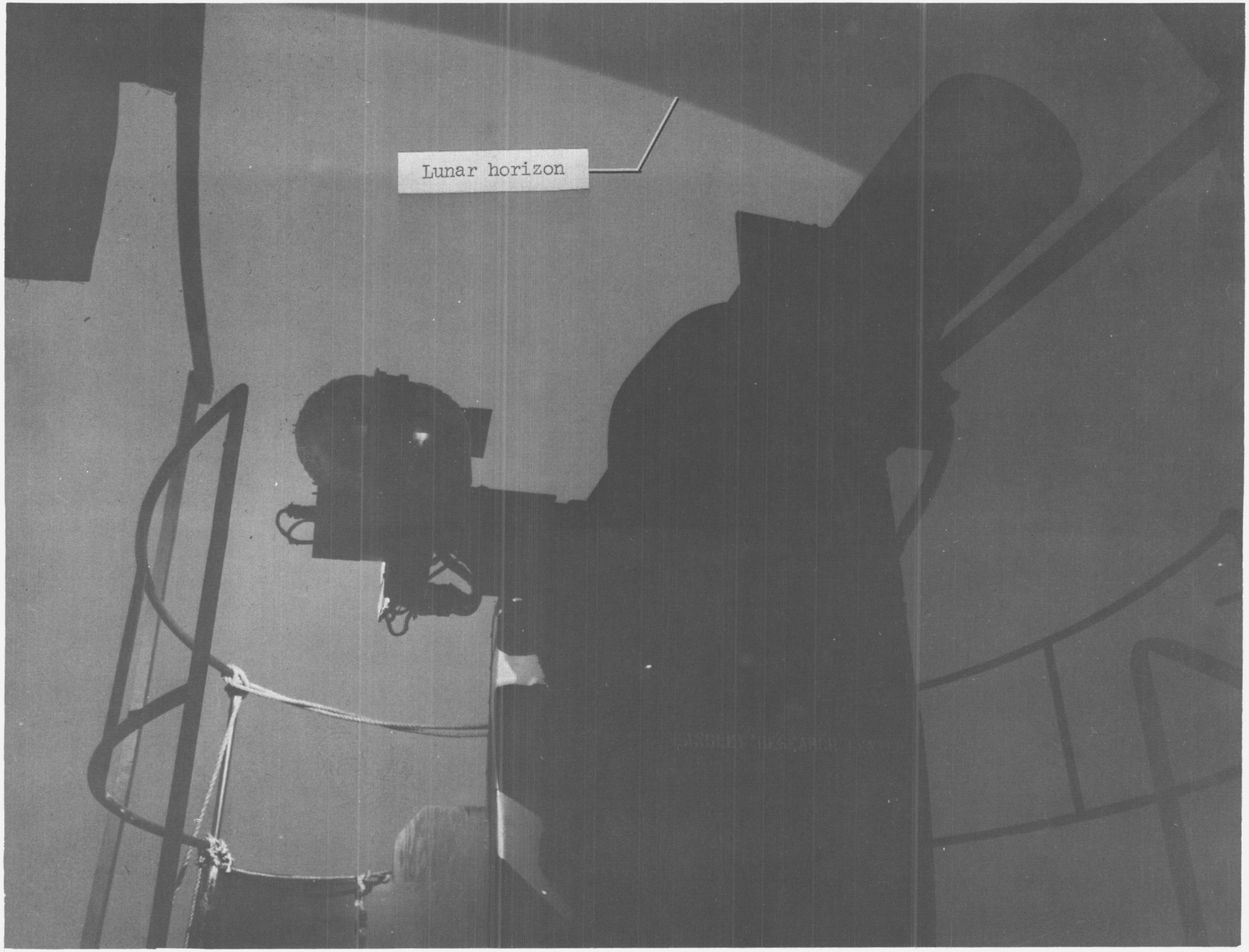
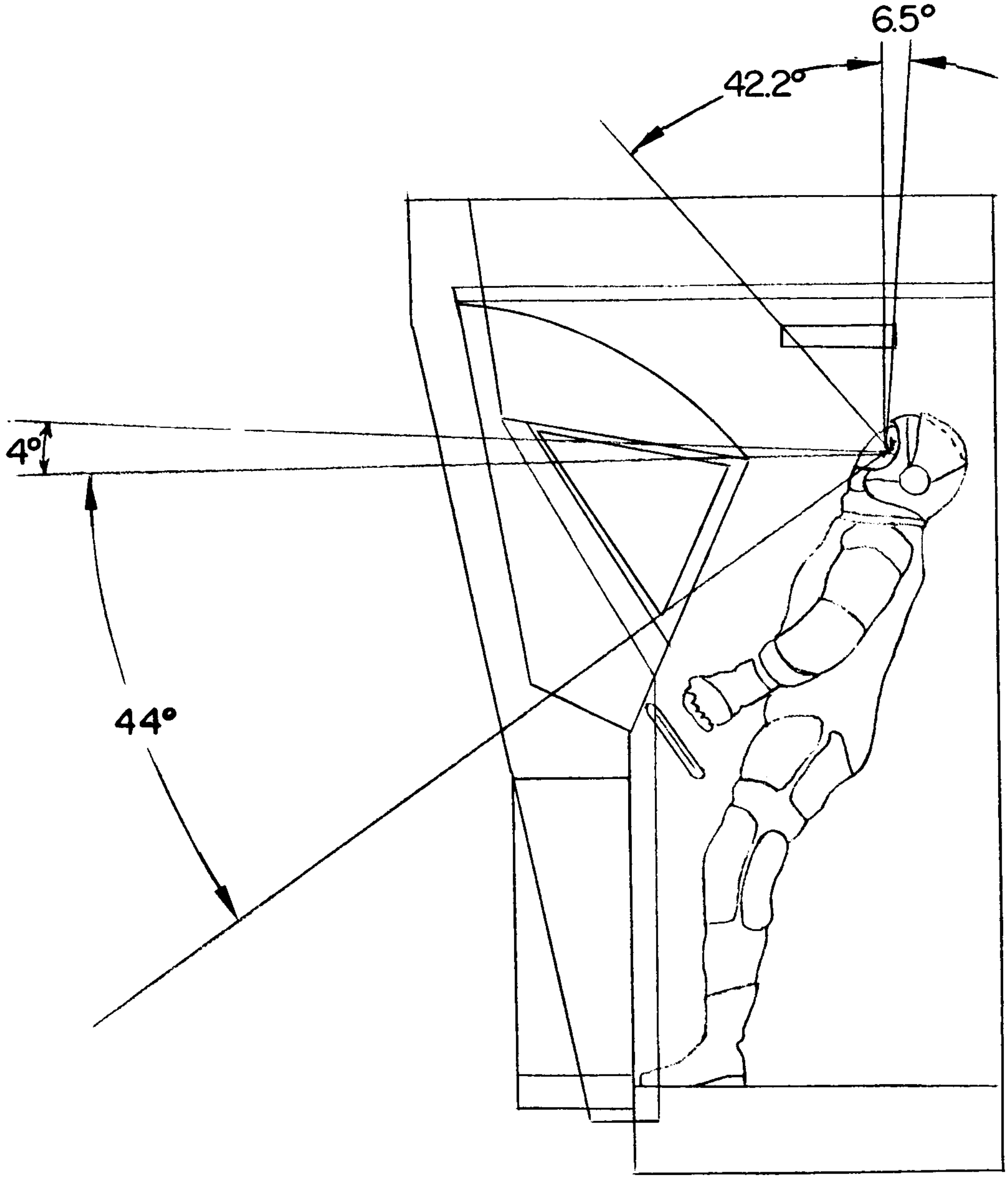


Figure 2.- Concluded.

L-66-10110.1



Angle of lateral view, deg			
Overhead		Front	
Left	Right	Left	Right
10	10	35	7.5

Figure 3.- Pilot's position in cockpit for lunar ascent. Pilot wears pressure suit and gazes through overhead window.

Figure 4.- Photograph showing pilot's position for lunar ascent. Pilot gazing through overhead window. L-66-10108

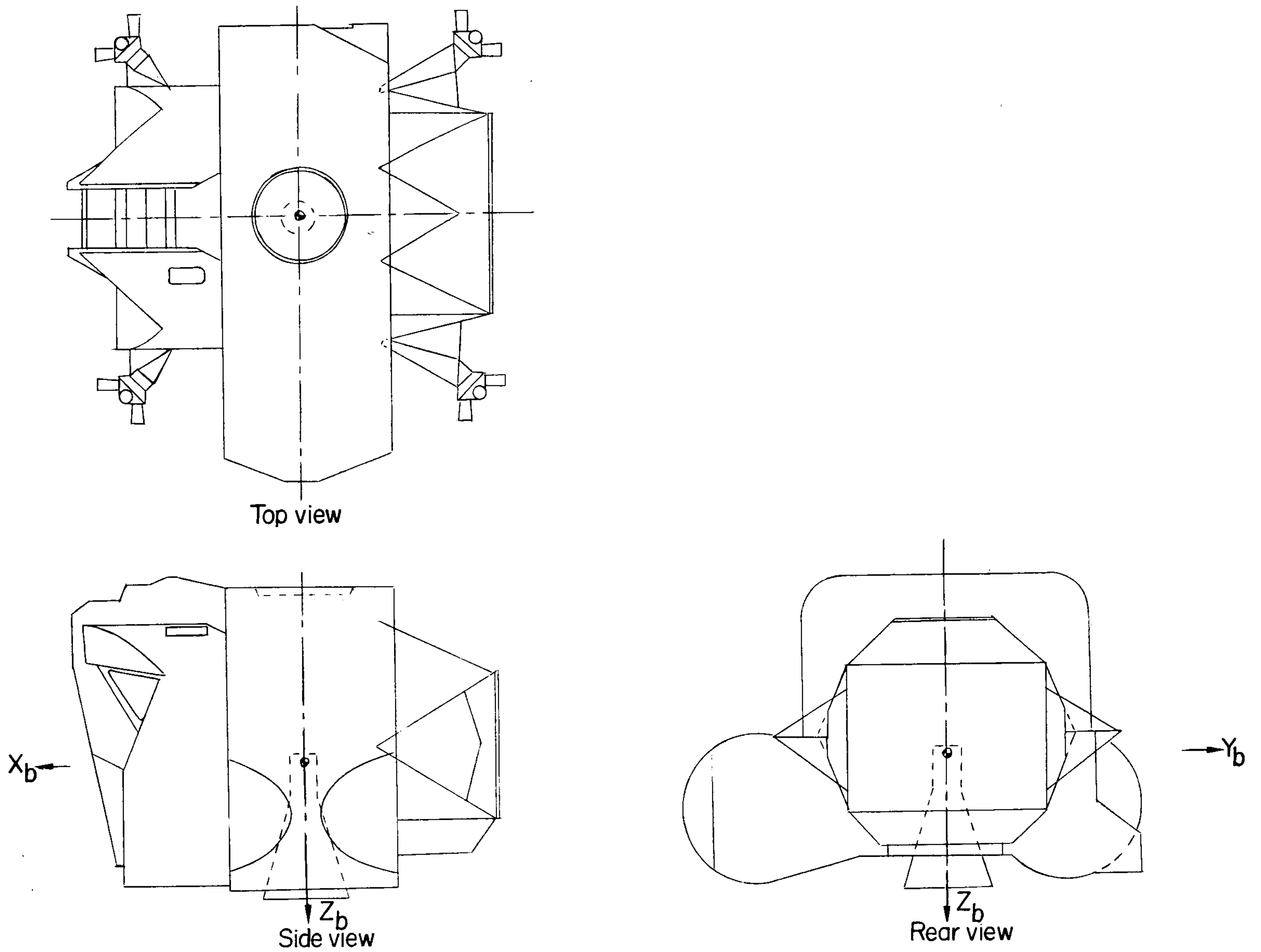


Figure 5.- General arrangement of LM.

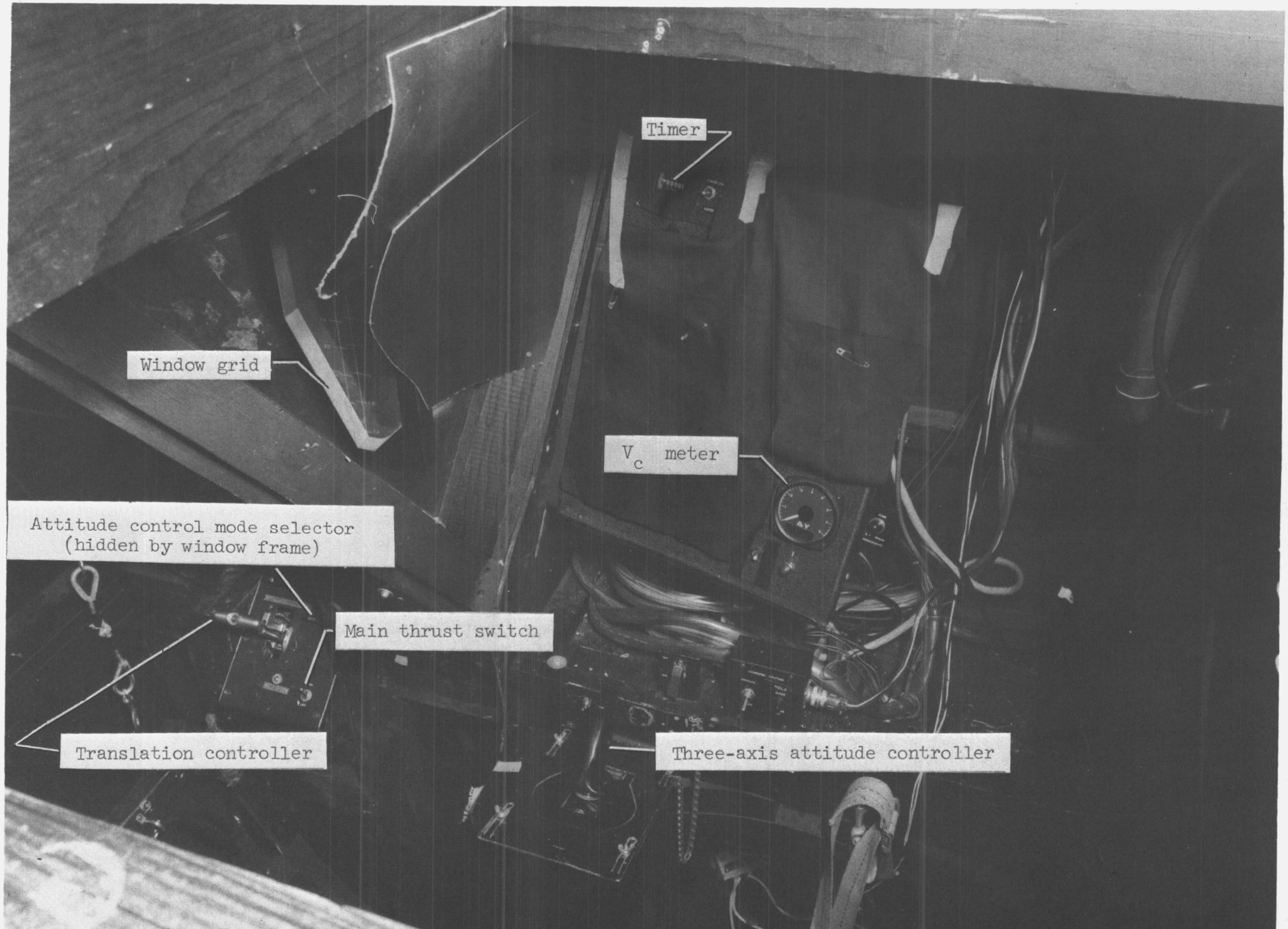


Figure 6.- Instrument display used for simulated ascent. L-66-7880.1

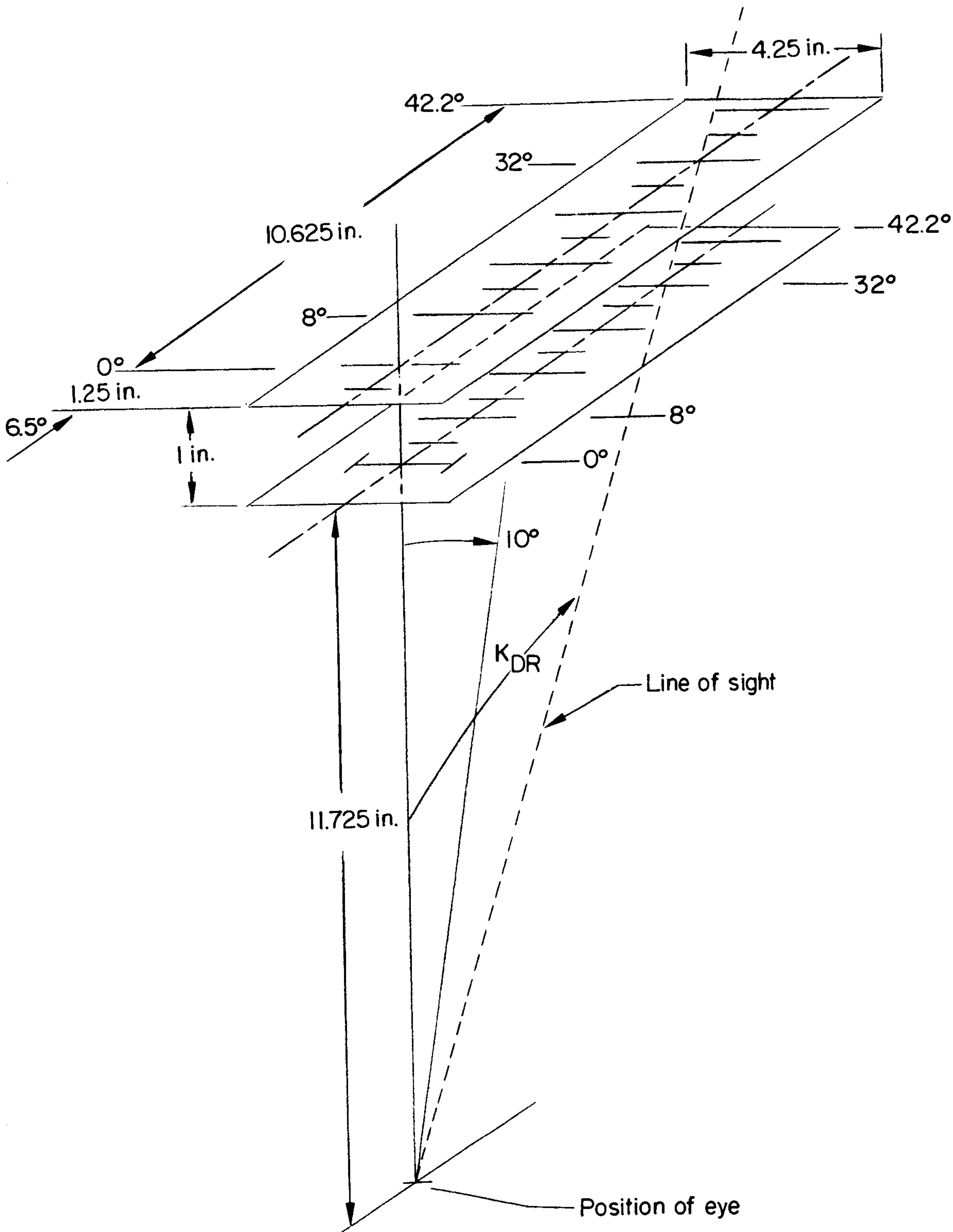


Figure 7.- Schematic drawing of double overhead-window grid.

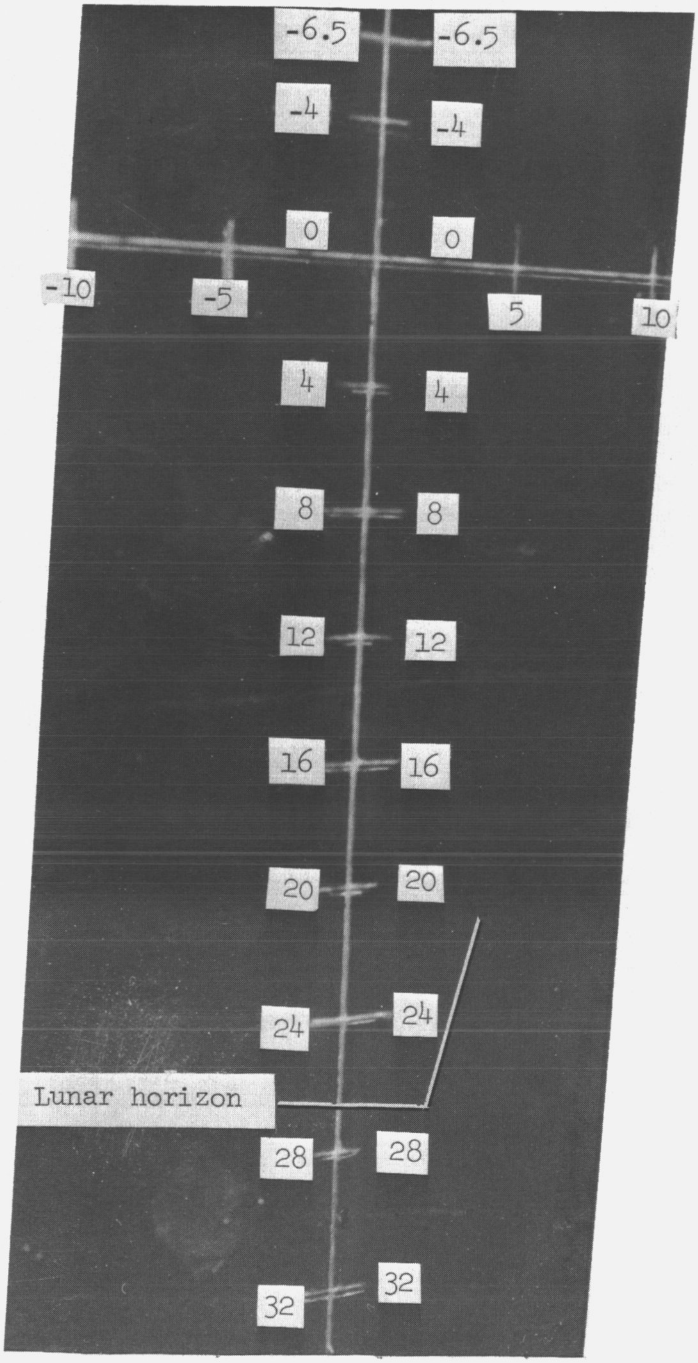


Figure 8.- Photograph of overhead-window grid and lunar horizon. Camera not located at pilot's design eye position. L-66-7882.1

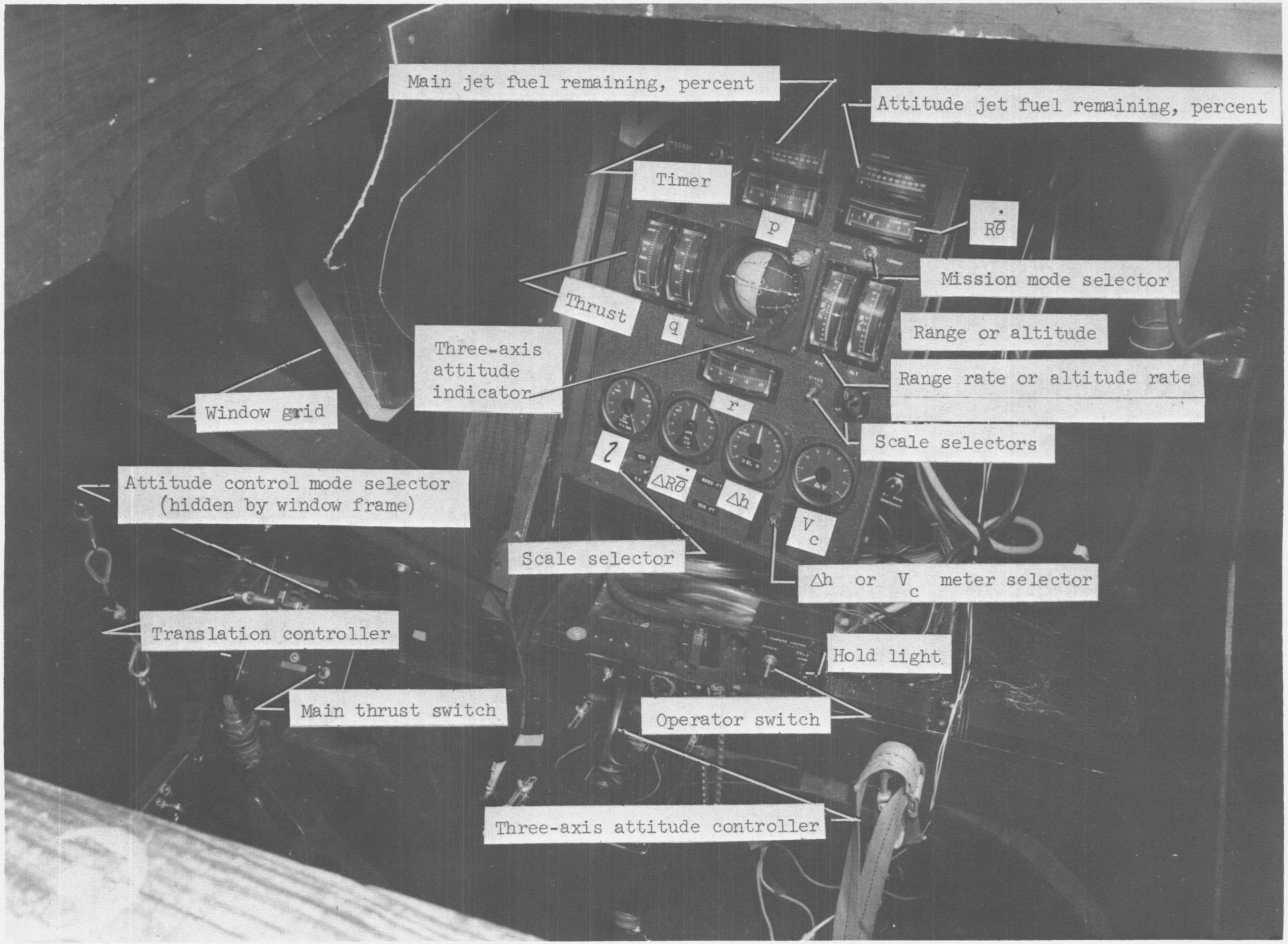


Figure 9.- Instrument display used for pilot training and fully instrumented flights. L-66-7881.1

NASA-Langley, 1968 — 21 L-5801